N76 11012

5.5 Wing-Tip Vanes as Vortex Attenuation and Induced Drag Reduction Devices

W. H. Wentz, Jr. and M. G. Nagati
Wichita State University

Summary

Analytical studies have been conducted to examine the feasibility of utilizing wing tip turbines to remove swirl from the wing trailing vortex, and hence reduce the potential for upset of following aircraft. Energy recovery from the turbines is also analyzed. A computer routine has been developed to permit rapid parametric studies of various tip turbine designs.

The studies show that the optimum turbine is a non-rotating set of vanes which reduce swirl and recover energy in the form of reduced overall configuration induced drag. A specific case study indicates a 23% reduction in induced drag for a rectangular wing of aspect ratio 5.33, operated at a lift coefficient at 1.0.

Introduction

The problems associated with the operation of small aircraft in the vortex wake of a large aircraft are well documented (Figures 1 and 2 and reference 1). Many solutions to reducing vortex induced angles have been proposed and tested. Most of these however, are achieved at the expense of added drag and hence increased fuel consumption and noise. The present research was undertaken to study the feasibility of a rather novel scheme for diffusing wing tip vorticity, and at the same time recovering energy from the vortex wake.

At least two similar techniques have been tested. The flow straighteners designed by Uzel and Marchman (ref. 2) and the "winglets" developed by Whitcomb (ref. 3).

The present study is concerned with evaluation of a wind turbine mounted in the center of the wing tip vortex core (Figure 3). The turbine is designed to remove the swirl component of velocity from the tip vortex, and to provide rotating shaft torque for conversion to propulsive or stored energy.

Analytical Method

The vortex core is modeled as shown in Figure 4 based upon Reference 4. The turbine is analyzed using the blade element theory of Reference 5. Basic blade element velocities and angles are shown in Figure 5. Since the function of the turbine is to reduce upset severity the blade is designed to remove the total swirl velocity at each radial station. This constrains the local induced angle to a value of one-half the local swirl angle, since half the downwash takes place downstream from the blade element.

It should be noted from the velocity vector diagram that not only is it possible to obtain a torque-producing force, but it is also possible to obtain a direct thrust force component which would appear as a reduced induced drag. The effect has been demonstrated by Whitcomb's winglets, but evidently the effectiveness of winglets in reducing vortex upset has not been evaluated. Uzel and Marchman evaluated fixed wingtip flow straighteners to reduce the vortex upset hazard, but their design evidently utilizes sharp-edged uncambered sections which cannot recover the leading section force which would produce thrust.

A computer program was developed to evaluate proposed designs in the present study. A simplified flow chart of the computational algorithm is shown in Figure 6. For simplicity, turbines utilizing constant chord blades were analyzed. The program was designed to adjust blade chord until the maximum angle of attack encountered along the span is between 14.5° and 15°. The effect of the constraint is to have a design near maximum unstalled lift coefficient condition, in order to minimize wetted area drag. Computer studies were made at a cost of less than $1 per configuration. Design conditions are given in Table 1.

Table 1. Design Conditions

Lift Coefficient	1.0
Aspect Ratio	5.33
Planform	Rectangular
Core radius	.01 (Span)
Maximum swirl velocity	.8 (Flight speed)
Vane section drag coefficient	0.010

Results

Results of the parametric studies of shaft power output as a function of rpm and diameter are shown in Figure 7. These data show that shaft power increases with diameter, and that rpm for maximum shaft power decreases as diameter is increased. Theoretical upper power limit occurs when shaft power equals wing induced power. Figure 8 presents net power, which is shaft power minus or plus the drag or thrust power, including blade section drag effects. These data represent a realistic accounting since blade section drag effects are included. For the values chosen for this study, a maximum net return of 35% of induced power is achieved for turbine diameters of 32 and 64 vortex core diameters. Thus turbine diameter ratios greater than 32 provide no added benefit. The most intriguing result, however, is that the optimum rpm is zero!

From a practical point of view, these results show that for virtually any turbine diameter, the net power recovery is nearly optimum at zero rpm. Since the shaft power is zero under such conditions, it follows that the significant task of the tip-turbine blades is to recover thrust directly. While designs involving blade diameters ratios of 32 do not seem practical, designs with diameter ratios in the range of 2 to 8 may be quite feasible.

An additional computer run was made with zero rpm, turbine diameter ratio equal to 8, and vane section drag coefficient increased from 0.010 to 0.013. All other parameters were retained as given in Table 1. This run showed that an induced power recovery at 23% was possible. This is believed to be a very realistic set of design conditions.

Blade twist distributions for selected configurations are shown in Figure 9. These results indicate that twist requirements pose no extreme fabrication problems.

Concluding Remarks

The present analysis has many limitations. Some of these are described and discussed below:

1. Vortex core rollup is not complete one chord behind the trailing edge. Therefore the assumed vortex velocity model is only approximate.

2. The present analysis does not account for mutual aerodynamic interference between the vanes and the wing. The vane lift will certainly produce induced velocities which will influence the main wing lift and hence vortex distribution. A more sophisticated analysis would include mathematical modeling of main wing and tip-vane vortex.

3. The present analysis does not account for off-optimum performance. It is reasonable to expect that operation at lower wing lift coefficient will adversely influence performance, since blade twist will no longer be optimum. The design criteria should protect against stalling of the vanes under such conditions, however.

4. The effect of the tip vanes is to replace a single concentrated vortex with a series of vortices emanating from the vane tips. No analysis has been made

of the trajectory of this new vortex system. If the new vortices coalesce, it is possible that the upset hazard to following aircraft might not be reduced.

Conclusions

1. Feasibility studies indicate that tip mounted multi-vane turbines can recover energy from a wing vortex wake, while simultaneously reducing the vortex swirl and presumably the upset hazard to following aircraft.

2. The studies show that a non-rotating array of vanes properly twisted will provide maximum net energy recovery, in the form of vane thrust.

3. Practical designs from the present study should be evaluated by wind tunnel tests to determine actual performance gains, as well as penalties for off-design operation.

References

1. Roberts, L.: On Vortex Wake Alleviation. In "The Future of Aeronautics," Proceedings of NASA University Conference on Aeronautics, University of Kansas, Lawrence, Kansas, October 1974.

2. Bower, R.E.: Opportunities for Aerodynamic-Drag Reduction. In "The Future of Aeronautics," Proceedings of NASA University Conference on Aeronautics, University of Kansas, Lawrence, Kansas, October 1974.

3. Uzel, J.N. and Marchman, J.F. III: The Effect of Wing-Tip Modifications on Aircraft Wake Turbulence. Report No. VPI E-72-8, Virginia Polytechnic Institute and State University, July 1972.

4. Scheiman, and Shivers: Exploratory Investigation of the Structure of the Tip Vortex of a Semispan Wing for Several Wing Tip Modifications, NASA TND-6101.

5. Dommasch, D.O., Sherby, S.S. and Connolly, T.F., Airplane Aerodynamics, Pitman Publishing, 1967.

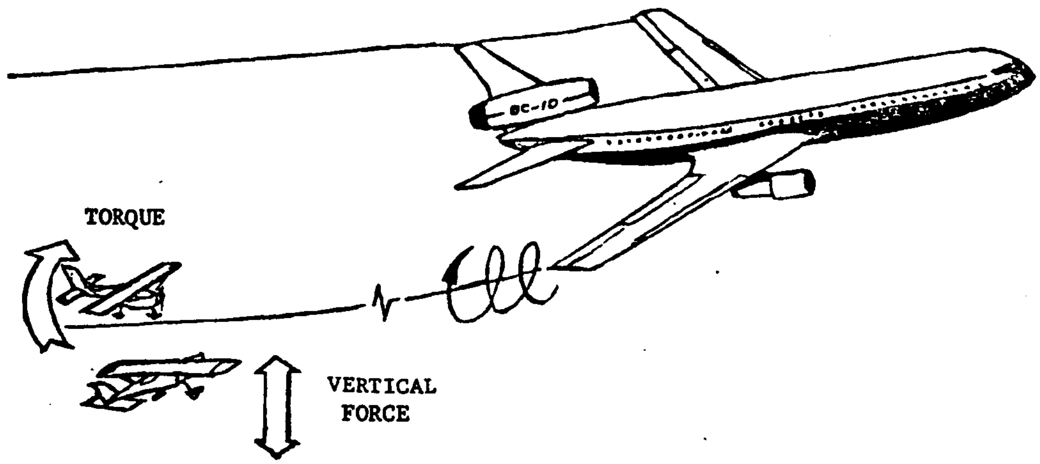


Figure 1. Vortex Upset Problem

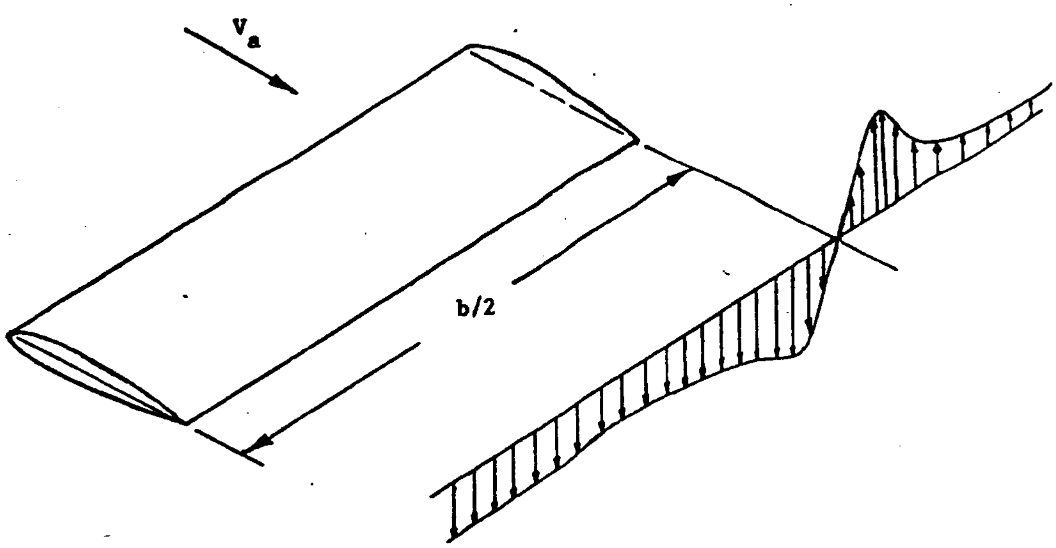


Figure 2. Wing Wake Velocities

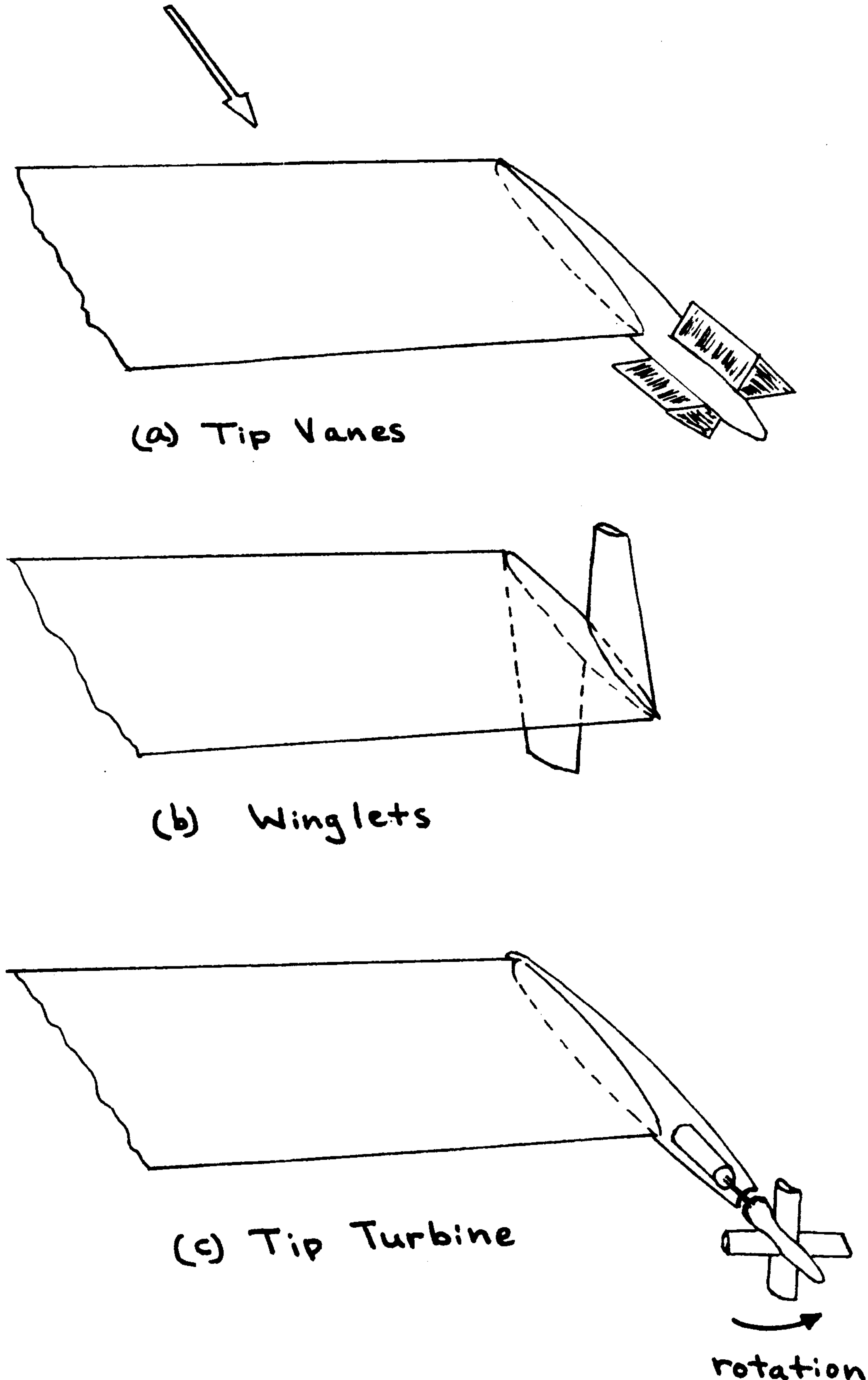


Figure 3. Wing-Tip Devices

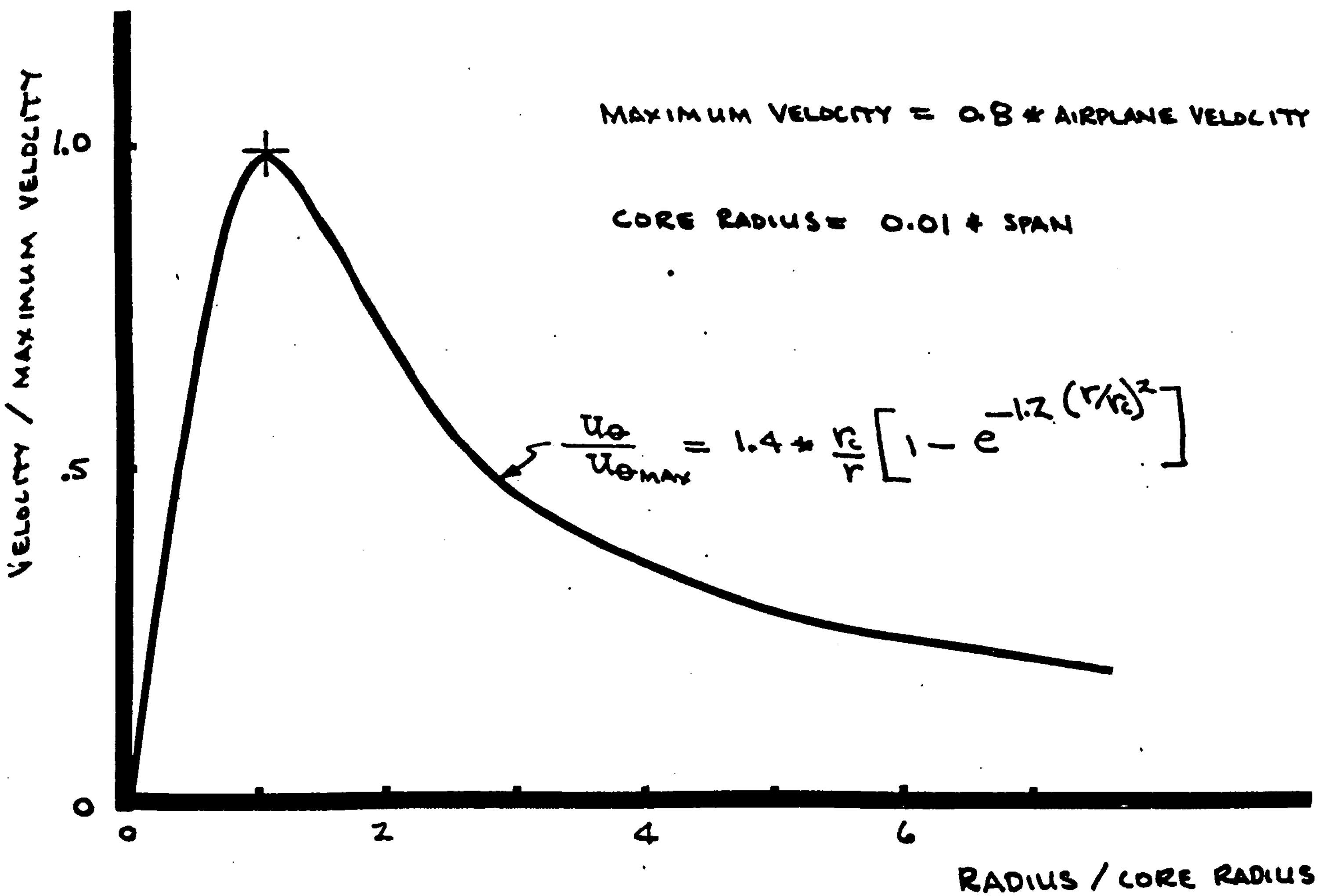
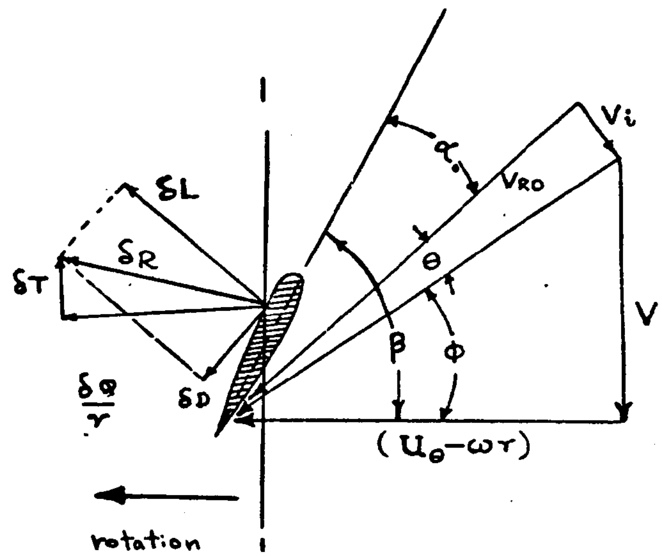


Figure 4. Vortex Velocity Distribution



Definitions:

β = blade pitch

ϕ = effective pitch

θ = induced angle

α_o = effective angle of attack

δL = section lift

δD = section drag

δR = section resultant force

δT = section thrust

$\frac{\delta Q}{r}$ = section torque/radius

V = airplane velocity

V_i = induced velocity

V_{RO} = relative velocity

U_θ = swirl velocity

ωr = blade velocity

Figure 5. Blade Element Velocities and Forces

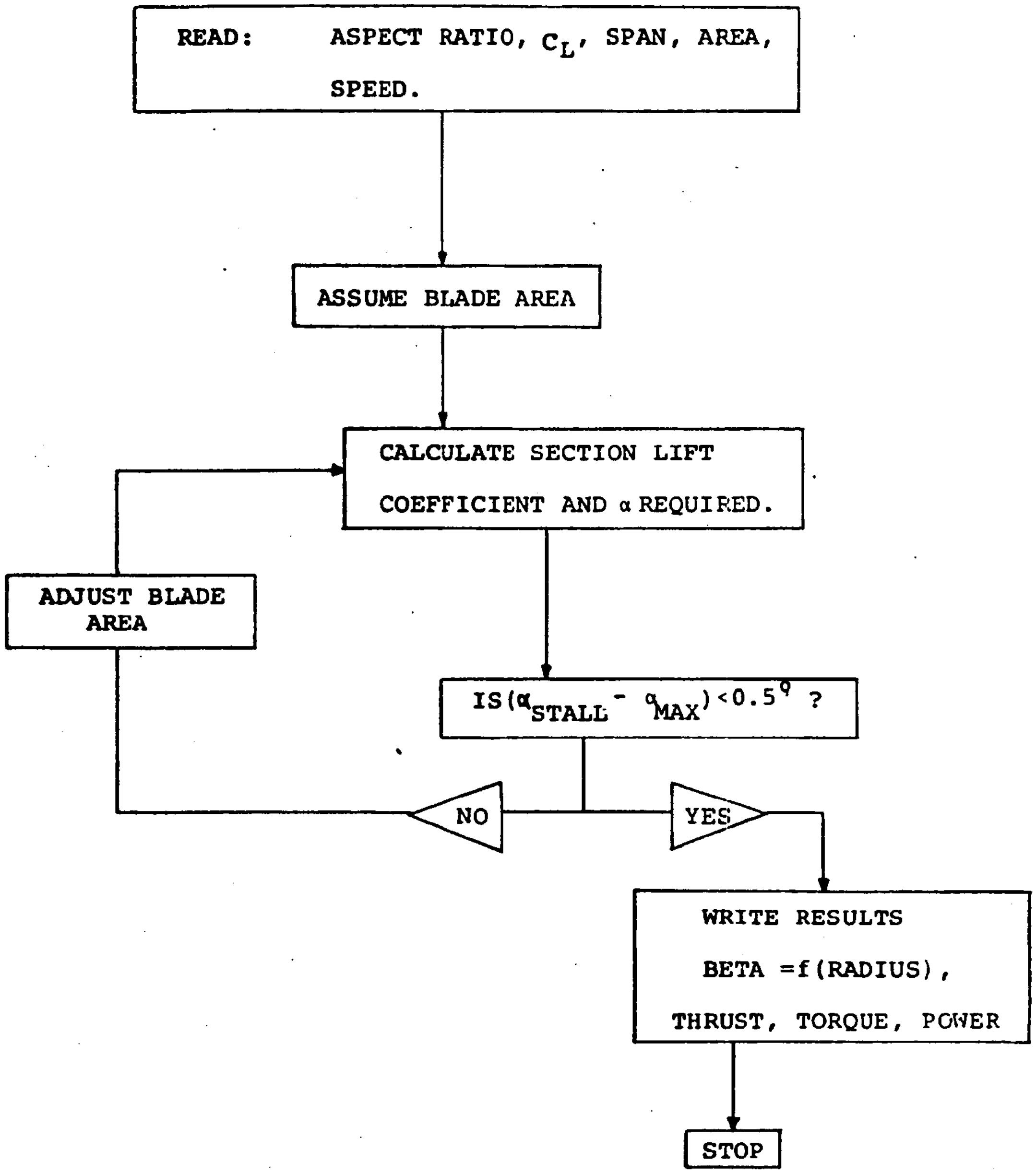


Figure 6. Tip Turbine Design Computer Program

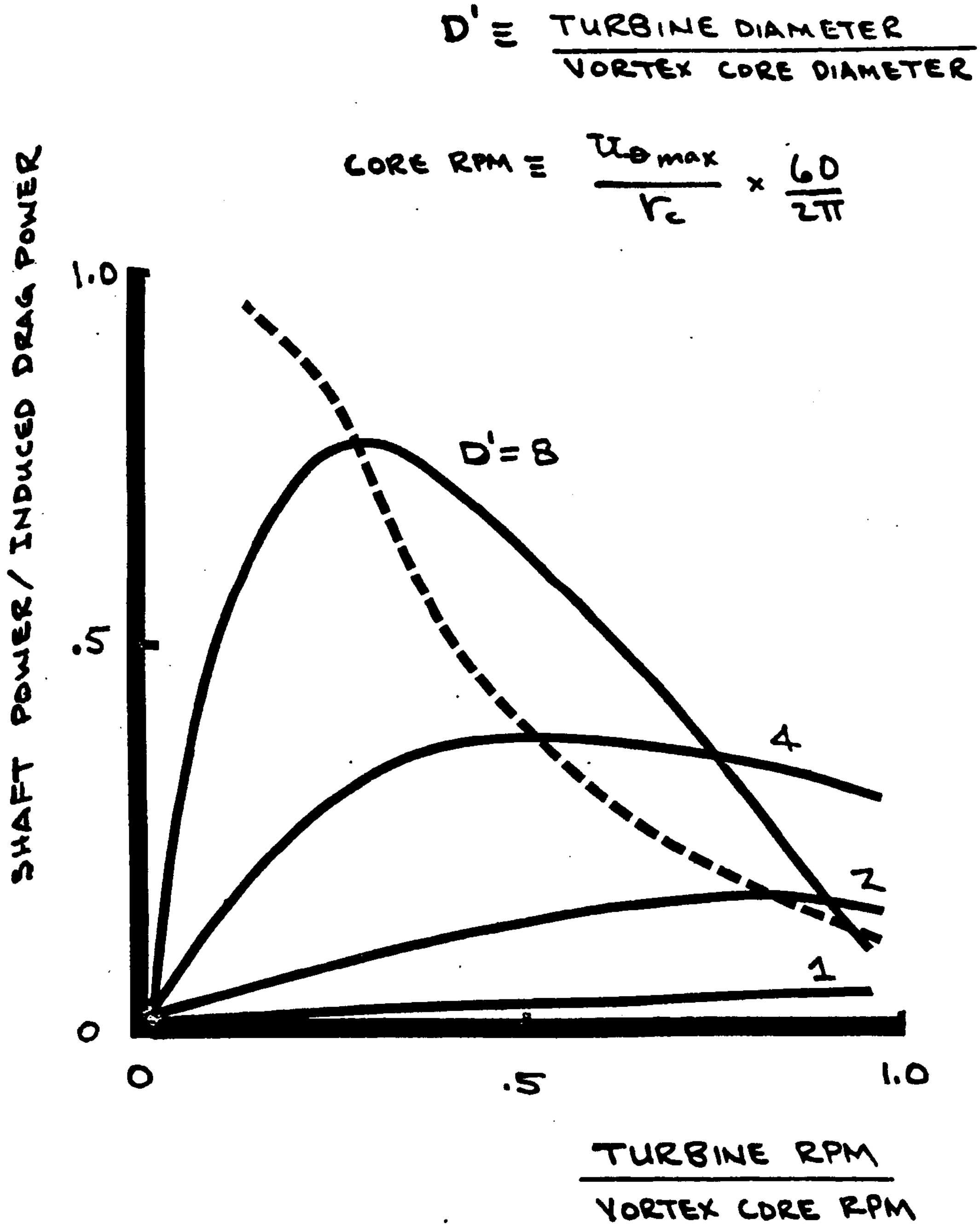


Figure 7. Shaft Power Ratio

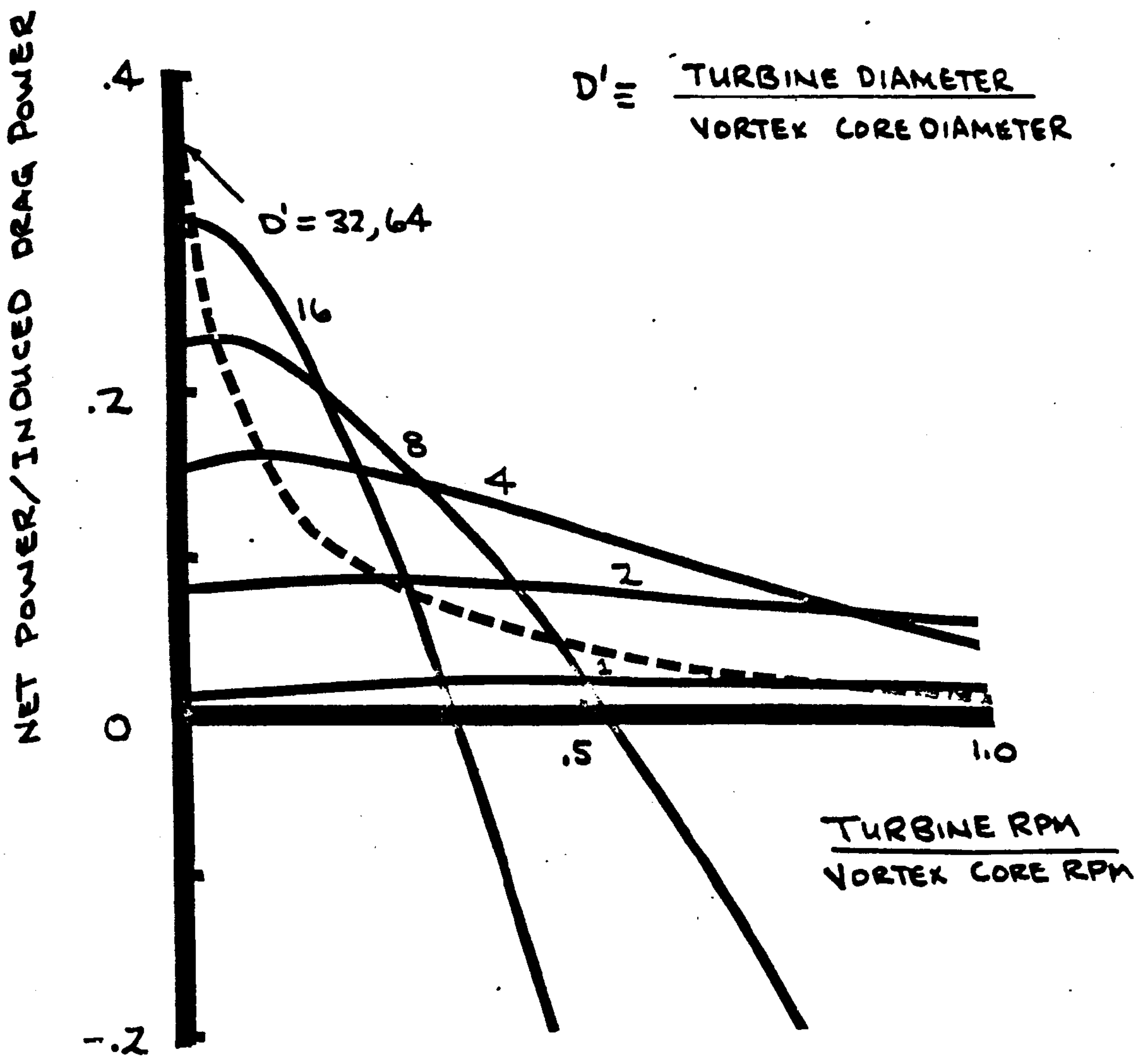


Figure 8. Net Power Ratio

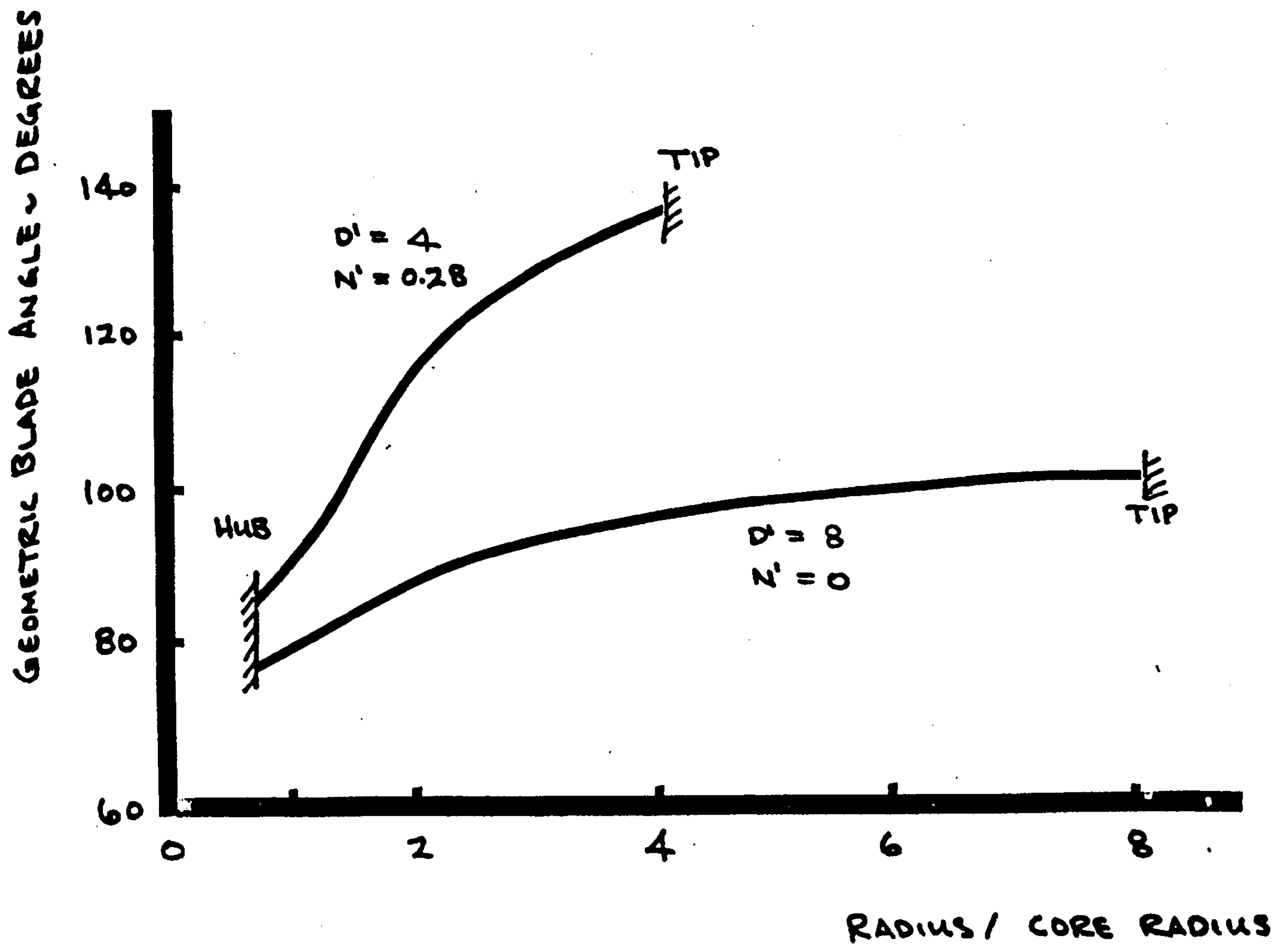


Figure 9. Blade Twist